Generation IV Roadmap: Fuel Cycles

Fuel Cycle Crosscut Group (FCCG)

Generation IV Roadmap Session
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FCCG Members

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– *Charles Boardman*	*General Electric (Retired)*
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– *Charles Forsberg * ******	*Oak Ridge National Laboratory*
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– *Jean-Paul Glatz*	*European Commission*
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– *Per Peterson*	*U. of California (Berkeley)*
– *Luc Van Den Durpel*	*Nuclear Energy Agency (OECD)*
– *Dave Wade **	*Argonne National Laboratory*

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Fuel Cycle Crosscut Group Charter

***Charter:** Examine fuel resource inputs and waste outputs for the range of potential Generation IV fuel cycles, consistent with projected energy demand scenarios. The span of fuel cycles will include currently deployed and proposed fuel cycles based on uranium and/or thorium.*

Responsibilities:

- *Define energy demand projections*
- *Project ore resource base*
- *Survey of cycle types: Identify technology gaps & Recommend R&D*
- *Determine range of energy supply achievable by Gen IV concepts within ore availability & waste arising constraints (Scenarios)*
- *Recommend fuel cycle parameters for all GenIV activities*

The FCCG Examined Implications Of A Global Nuclear Energy Enterprise

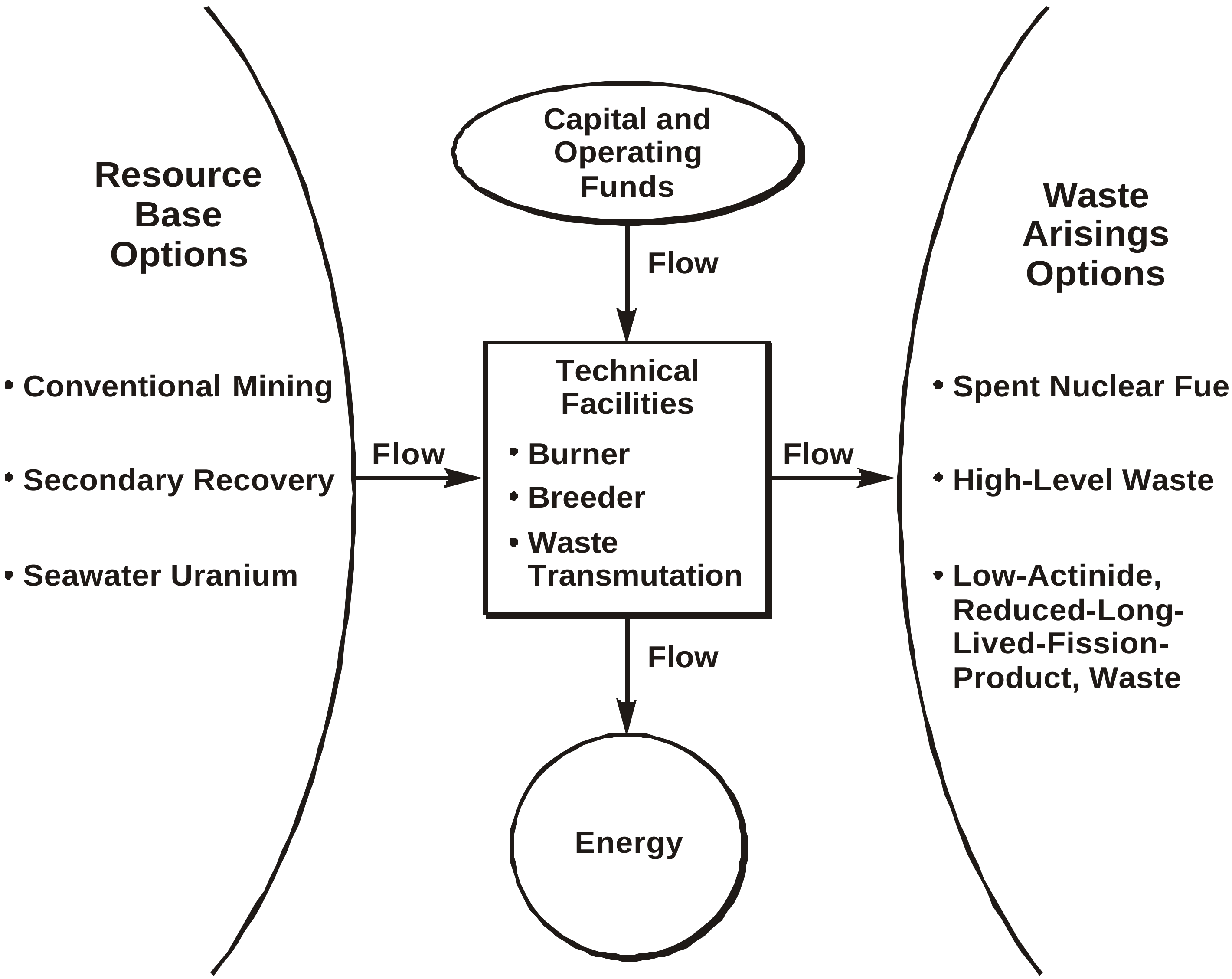
- *World demand growth projections for nuclear energy (Midcase)*

Now:	*350 GWe*	
2050:	*2000 GWe*	*World Energy Council/IIASA Case B*
2100:	*~6000 GWe*	*Growth at ~20-25 year doubling time*

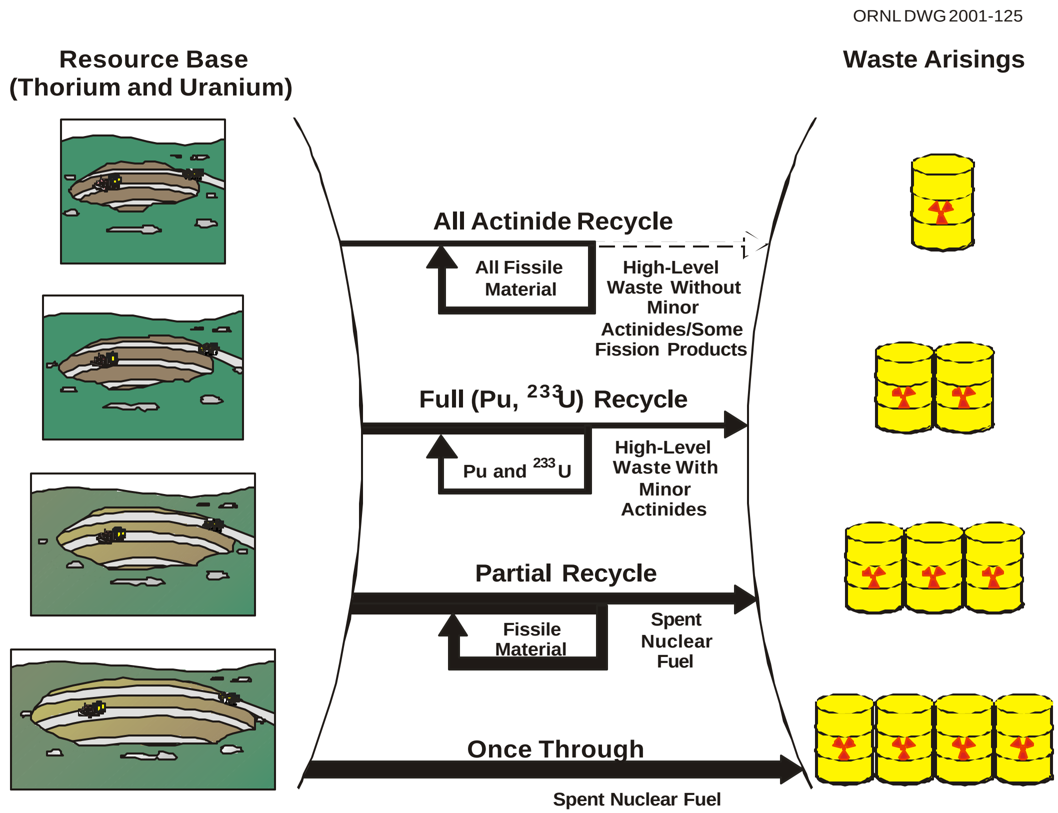
- *Mainline projections exclude other applications of nuclear power (hydrogen, heat, etc.)*

- *Time Frame to 2100*
  - *GenIV considers reactors deployable by 2030*
  - *Reactor lifetime projected to be 60 years*
  - *Fuel cycle must consider lifetime fuel demand and waste generation*

The Fuel Cycle in the Abstract



Four Alternative Fuel Cycles Have Been Defined



OAK RIDGE NATIONAL LABORATORY
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UT-BATTELLE

The Key Fuel Cycle Issues Are Associated With Long-Term Sustainability

- ***Sustainability I: Uranium/Thorium Resources***

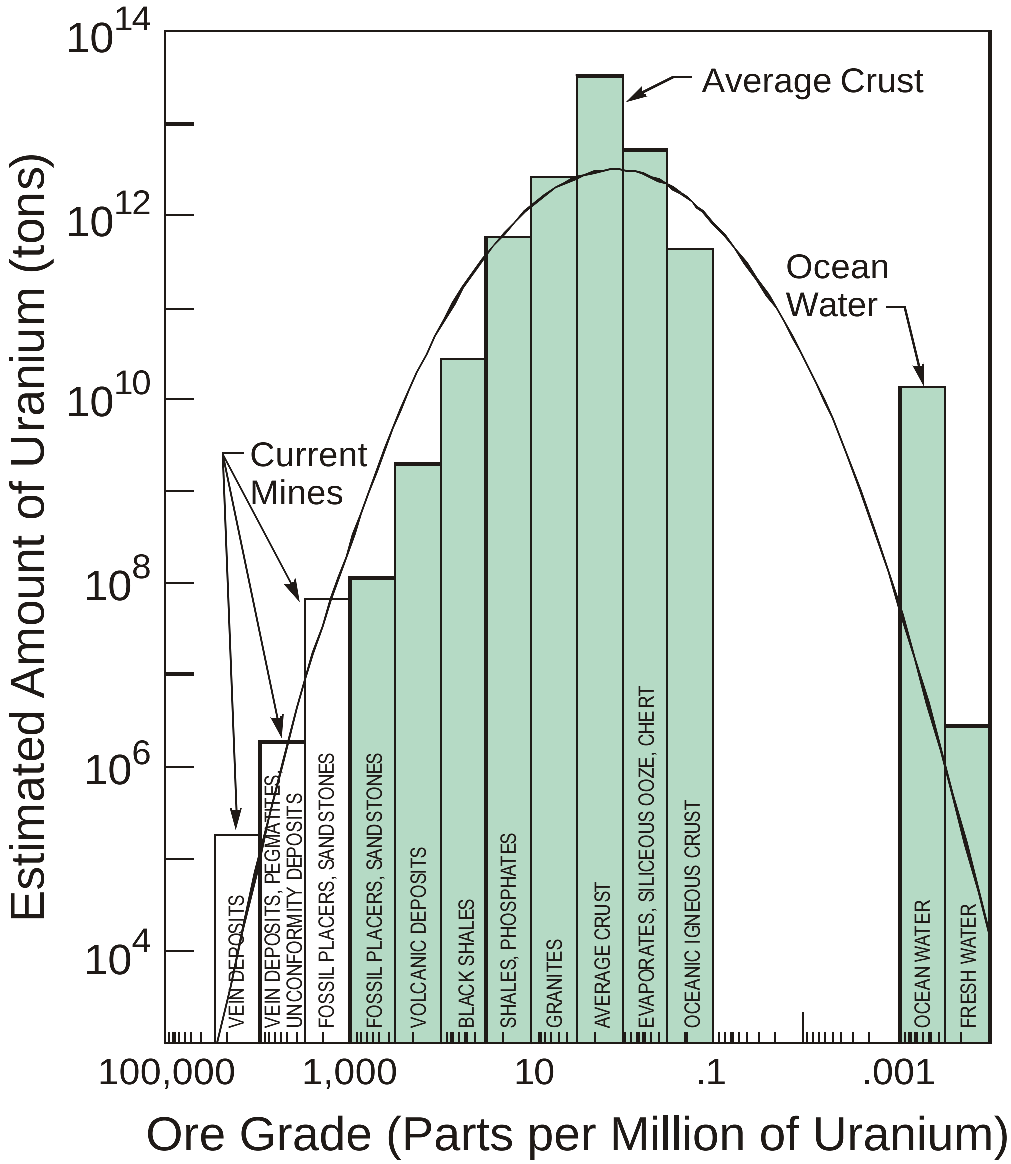
- ***Sustainability II: Waste Management***

- ***Sustainability III: Non-proliferation***

Sustainability I: Cost and Environmental Impacts, Not Resource Availability, Limit Uranium And Thorium Resources

- *Two Periods of Ore Exploration*
  - *1950's (Cold War Driven)*
  - *1970's (Oil Shock Driver)*
  - *Current Glut of Uranium – Negligible Prospecting Going On*
- *Three components in current estimates of ore*
  - *Redbook Known + Speculative Reserves:*
    4.5 + ~10-15 million tonnes U
  - *Geologic estimates to crustal abundance (see Figure)*
  - *U in Seawater in parts per billion (Billions of tonnes)*
- *Harvesting Ore of 10 fold reduction in assay:*
  - *300 fold increase in reserves*
  - *10 fold increase in mining per kg of uranium*
  - *Cost and impacts determined by economics of scale and technological advances*
- *Sustainable ore availability is not the issue: Cost and ecological disruption are the issues and both will be impacted by:*
  - *Long-term competition between lower grade ores and recycle of discharged SNF*
  - *Differences in repositories with wastes from once-through and recycle fuel cycles*

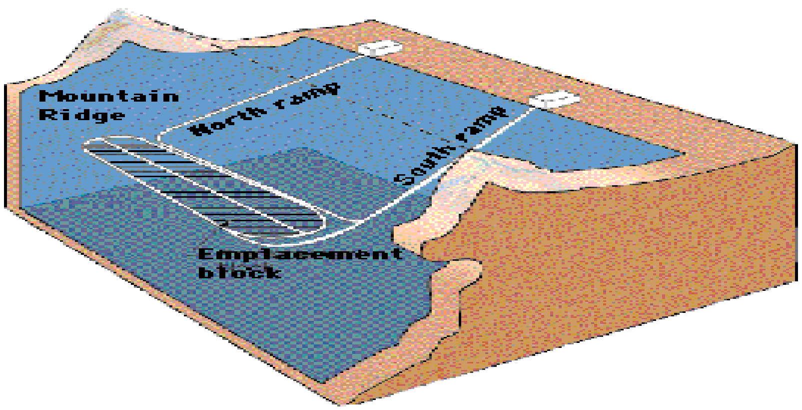
Distribution of Uranium in the Earth's Crust



Sustainability II: Repository Availability May Be The Major Constraint To Nuclear Energy: Choice of Fuel Cycle Impacts The Repository

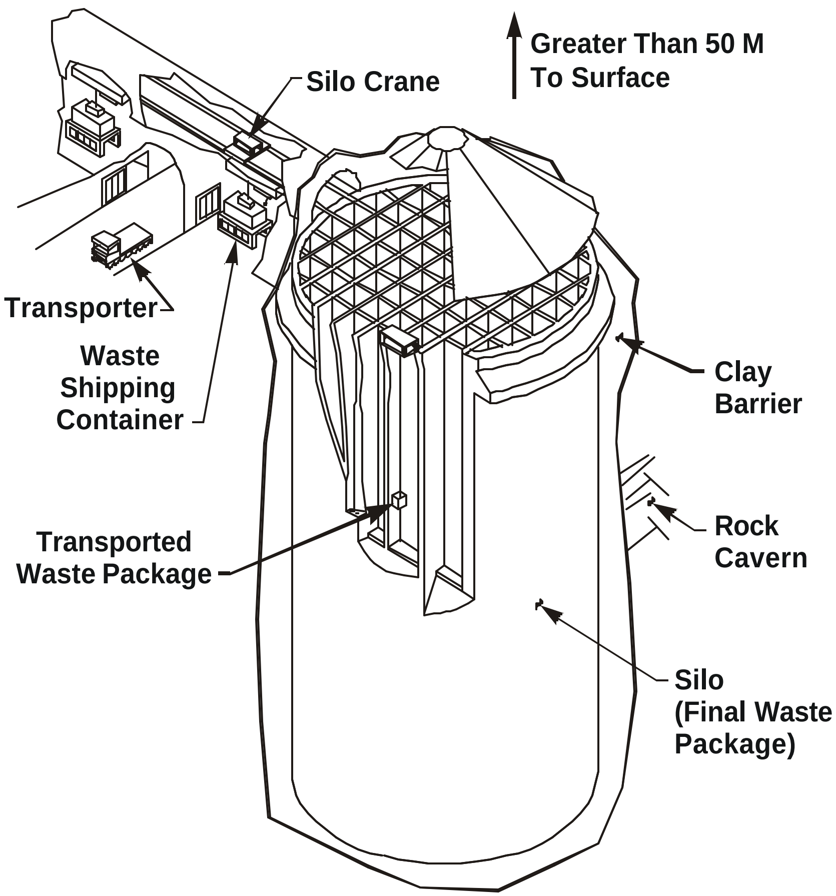
- *Technical waste characteristics strongly impact repositories*
  - *Decay heat (size and costs)*
  - *Radio-toxicity (licensing and public acceptance)*
  - *Volume and waste form (requirements and cost of waste packages)*
  - *Fissile mass (safeguards and nuclear criticality)*
- *Example: Once-through versus P/T repository options*
  - *Decay heat controls repository size*
    - » *Repository temperatures limited to reduce potential for radionuclide releases*
    - » *Waste packages spread-out over large distances to reduce temperatures*
    - » *P/T destroys actinides—the long-lived heat generators*
  - *SNF and P/T repository designs would be very different*
    - » *SNF repository design decay heat controlled*
    - » *P/T repository design option to store wastes or separate ^{90}Sr/^{137}Cs before disposal and use low-heat repository*

Conventional Repository Size Is Controlled By Decay Heat



- ***High temperatures degrade repository performance***
- ***Temperature limited by limiting the density of waste***
  - ***>10,000 waste packages***
  - ***>100 km of tunnels***
- ***Repository size can be reduced by long-term waste storage***
  - ***Surface storage***
  - ***Ventilated repository***

Lower Decay Heat Loads From Some Fuel Cycles May Allow Much Smaller Repositories



- *The key is to reduce decay heat from ^{137}Cs, ^{90}Sr, and actinides*
- *If actinides are destroyed (P/T), long-term decay-heat eliminated*
- *Many options for cesium and strontium management*
  - *Separate and store*
  - *Store waste until cool*
- *A few underground silos replace kilometers of tunnel and thousands of waste packages*
- *A design without ^{137}Cs, ^{90}Sr, and actinides is not decay-heat controlled*

Sustainability III: Different Fuel Cycles Have Different Non-proliferation Strategies

- ***Three strategies have been proposed***
  - ***Once-through (LWR, HTGR)***
    - ***No processing***
  - ***Conventional Recycle (LWR-OX, LM)***
    - ***No clean plutonium***
    - ***Hot fuel***
  - ***Low weapons-usable inventory (Molten salt and gas core reactors)***
    - ***$^{233}U/^{232}Th$ denatured fuel cycle; ^{242}Pu primary weapons-usable isotope***
    - ***Hot fuel with no off-site fissile materials***
- ***Basis for comparing cycles is not well established***

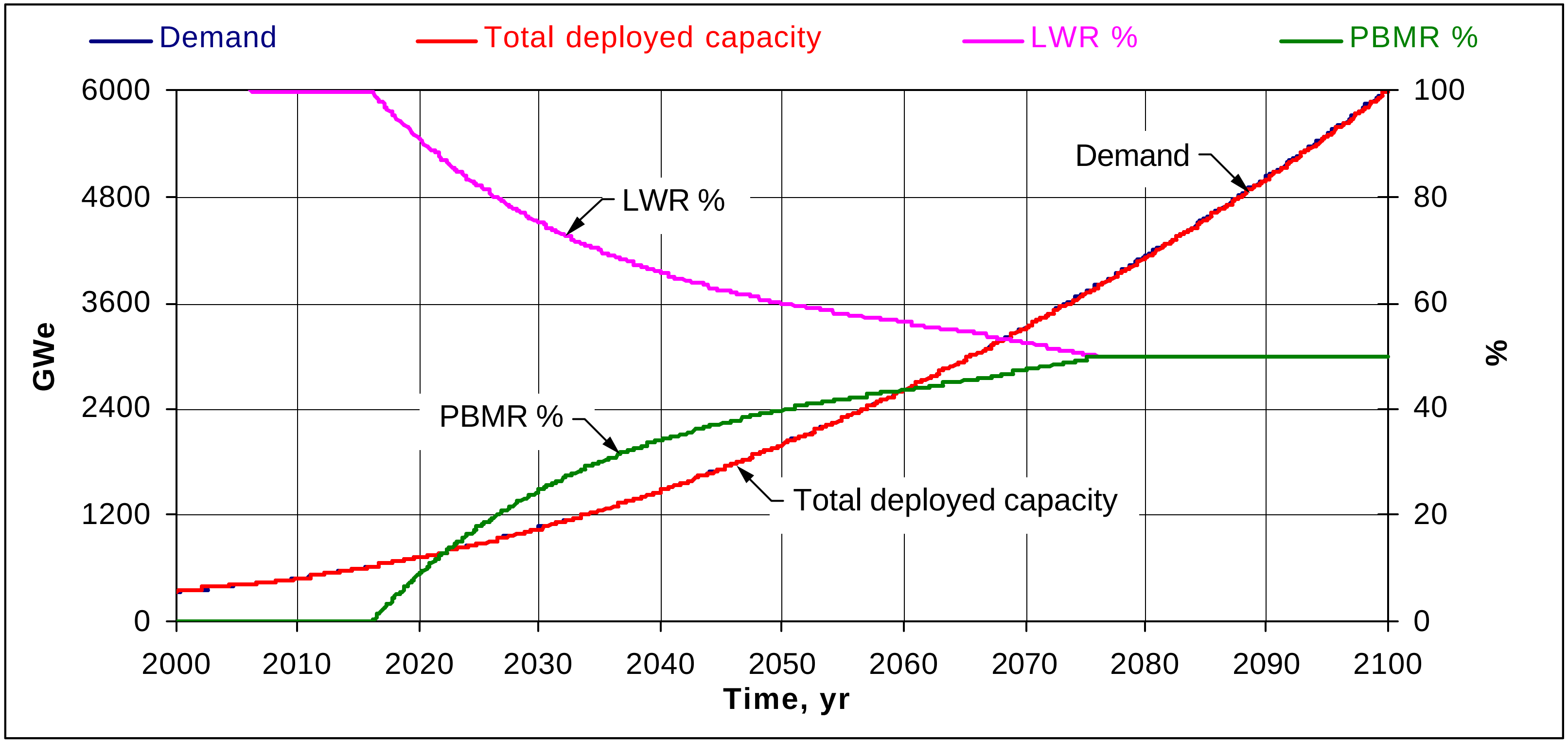
Nuclear Energy Scenarios Are Being Evaluated To Understand The Impacts Of Different Fuel Cycles

- ***Dynamic scenarios from year 2000 to year 2100***
- ***Scenarios run for generic fuel cycle types***
- ***Performance is being evaluated against sustainability Goals (I to III)***
- ***Idealized cases to serve as indicators of physically achievable performance against Gen-IV sustainability goals***
  - ***Model transitions from current deployments***
  - ***Model symbiotic energy parks of multiple Gen-IV concepts filling different market niches/functions***

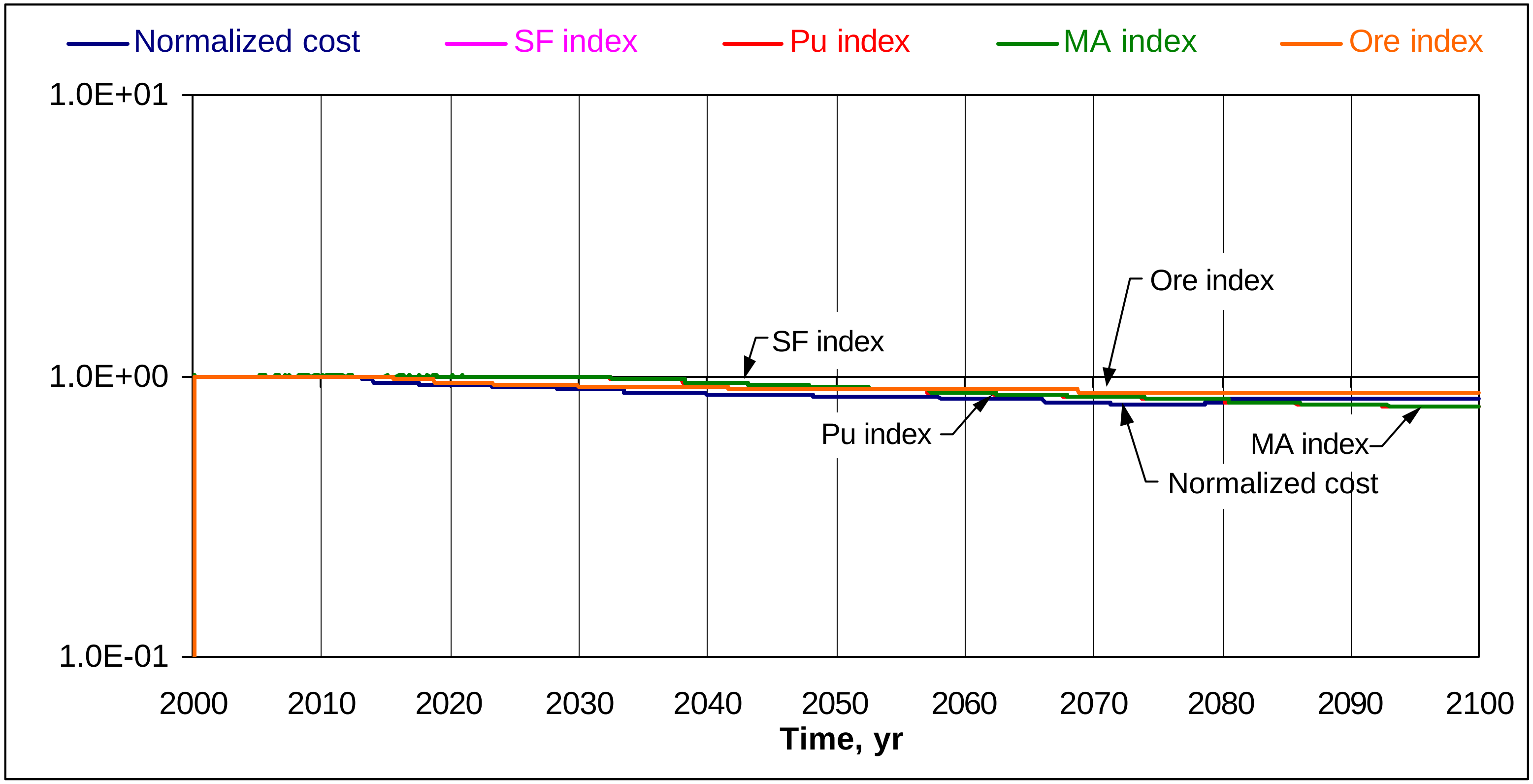
Fuel Cycles Being Examined

- ***Once Through***
  - ***LWR***
  - ***LWR and PBMR***
  - ***LWR/thorium***
  - ***LWR/PBMR with electricity and hydrogen production***
- ***Partial Recycle***
  - ***LWR to LWR (OX)***
  - ***LWR to Candu (DUPIC)***
- ***Conventional Recycle (plutonium and ^{233}U Recycle)***
  - ***LWR/FR with excess fissile to LWR***
  - ***LWR/FR with excess fissile to PBMR***
- ***Recycle Including Higher Actinides***
  - ***LWR/FR***
  - ***LWR/FR/MSR***
  - ***LWR/MSR***

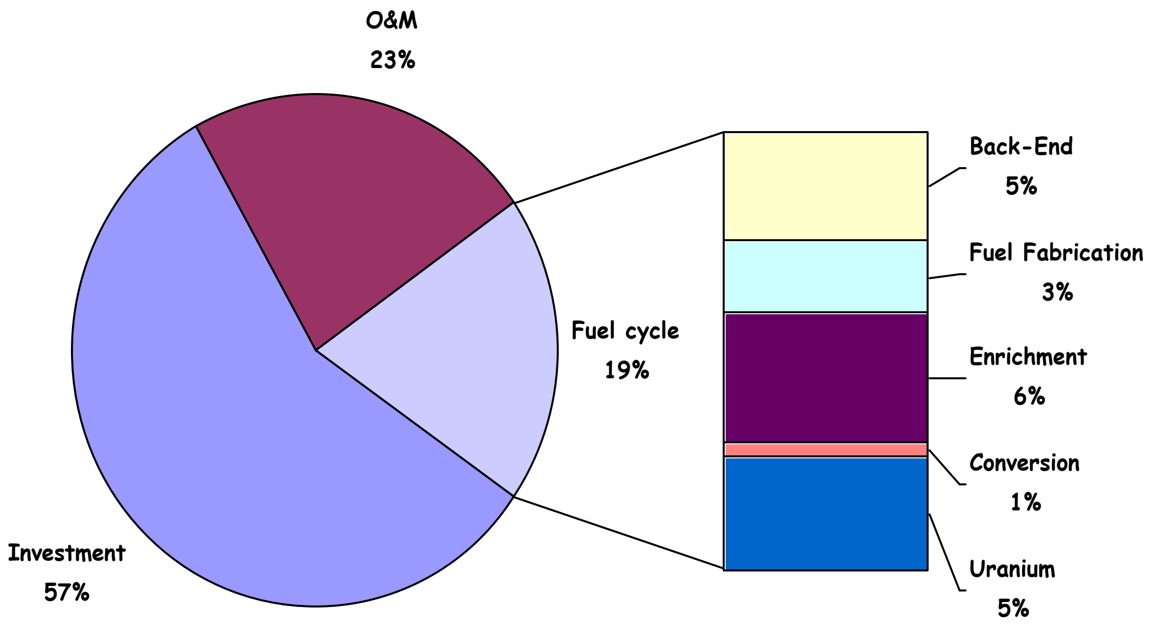
LWR/Pebble Bed Modular Reactor Deployment With Ultimately A 50/50 Mixture



Relative Mass Flows For LWR/Pebble Bed Modular Reactor Deployment Versus Once-Through LWR Cycle Shows Small Global Fuel Cycle Impacts



The Small Impact Of The Fuel Cycle On Nuclear Economics Provides A Degree Of Freedom For Future Nuclear Systems



Summary

- ***Long-term sustainability will determine the choice of fuel cycles***
  - ***Uranium/thorium resources***
    - » ***Significant resources available***
    - » ***Environmental and economic factors, not availability, limit quantities***
  - ***Waste management***
    - » ***Major public acceptance issues***
    - » ***Many options but some of the options are only partly understood***
      - ***Partitioning and transmutation of wastes***
      - ***Long-term storage before disposal***
  - ***Non-proliferation***
- ***Economics do not strongly constrain the choice of the fuel cycle—other factors may impact choices***